ULTIMATE BEAMS and BEYOND BEAMS

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Snowmass 2021 AF1 Workshop Session 3:

Physics Limits of Ultimate Beams

January 22, 2021

OUTLINE

1. *Introduction: Background and a Skeptic's View*
2. *Classical Linear Collider Scaling: Ultimate Beams for 5 TeV c.m. e-e+ Collider*
3. *Challenges "Beyond the Standard Model"*

   → *"Early" and "Dark" Universe, Cosmic Gravitational Background, Breakdown of Gauge Symmetries, Quantum Gravity,….*

4. *Promise of Re-orienting Accelerator Technologies away from Colliding Particle Beams towards High Energy Single Particles Breaking Vacuum or Other Precision Quantum Sensors*

   → *Cavity-Qubit Detection of "Dark" sector*

   → *Atomic Interferometric Probe of Early Universe*

   → *Other Quantum Sensors: NMR,NV Centers, Dirac-Weyl*

5. *Outlook*

BACKGROUND

- *Mei asked me to talk about 'quantum limits' to ultimate beams*
- *As far as I know, taken singly without collisions, most beams are far from their quantum limits*
- *Limits appear when we consider colliding beams*
- *In electron-positron linear colliders, they appear as 'radiative' effects of 'Beamstrahlung', coherent pair creation and strong interaction QCD backgrounds, but still far from the limits on 'final focus' spot size arising from the 'Oide' effect (statistical nature of emitted photons of synchrotron radiation arising from severe bending during final focus). These 'radiative' effects limit electron-positron linear colliders beyond 5 TeV c.m. energy*
- *In electron-positron circular colliders, the maximum energy reach is limited by synchrotron radiation in circular colliders, typically a maximum of a modest fraction of a TeV, approximately 300 GeV c.m collision energy for 100 km circumference ring.*
- *In circular Hadron Colliders, most limits arise from classical nonlinear dynamical phenomena of phase-space diffusion and particle loss due to very high order nonlinear resonances introduced by Coulomb interaction forces of intense beams in collision. This has been the case for all hadron colliders to date:*

A skeptic's view: There is more to life than the obsession with 'Higgs' and the 'Neutrino" via colliders and accelerator beams!!

I will focus on CLASSICAL ***LINEAR COLLIDER Scaling and why we should consider going beyond colliding particle beams, while re-orienting and applying all advanced accelerator technological elements of vacuum, lasers, superconducting cavities, superconducting magnets etc. in novel experimental set-ups not requiring colliding beams and still be relevant for addressing fundamental particle physics questions beyond the 'Higgs' and 'Neutrino".***

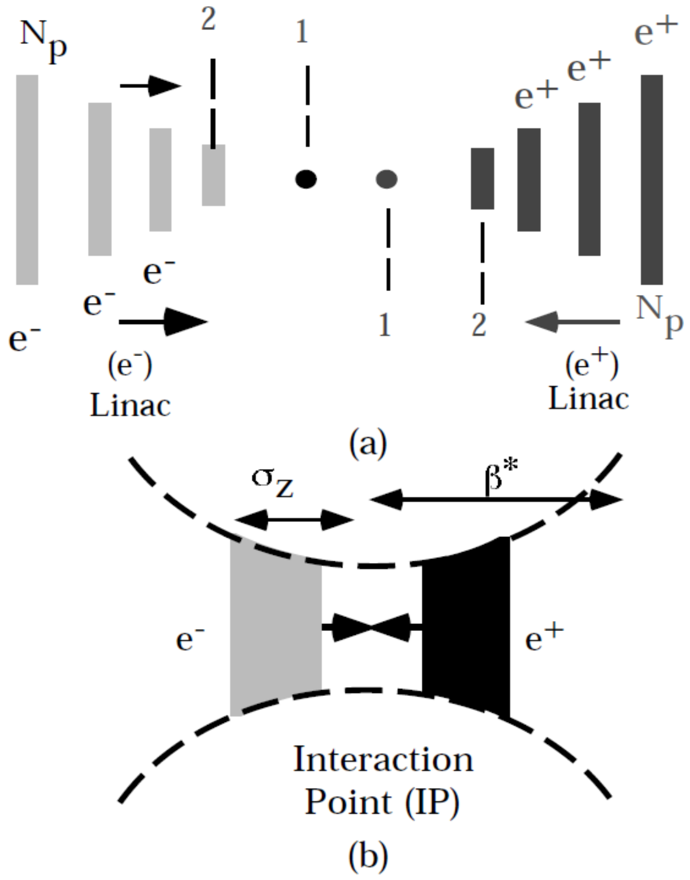
Vladimir Shiltsev will have a lot to say about typical collider scalings, power levels involved, cost scalings, energy and luminosity scalings etc.

Unfortunately, not much has progressed since 1990s in the linear collider development except for tremendous progress in superconducting RF, but the basic scaling and limitations were already considered in the 1996 DPF/DPB Snowmass studies. I will remind ourselves of the issues then and persisting even today about ultimate limits in electron-positron beams in linear collision.

CLASSICAL *LINEAR COLLIDER* DESIGN

SCALINGS

A TYPICAL COLLIDER CONFIGURATION
at
INTERACTION POINT



'H': Luminosity enhancement due to 'beam self-pinching', high luminosity coming at the expense of high average beam power

$$L = \frac{fN^2}{4\pi\sigma_y^{*2} R} H$$

$$P_b = 2\left(\gamma mc^2\right)(Nf) = \eta P_w .$$

The 'radiative effects' at the IP affect the charged particle beam phase space (hence luminosity and collision kinematics) and generate undesirable backgrounds in the detector:

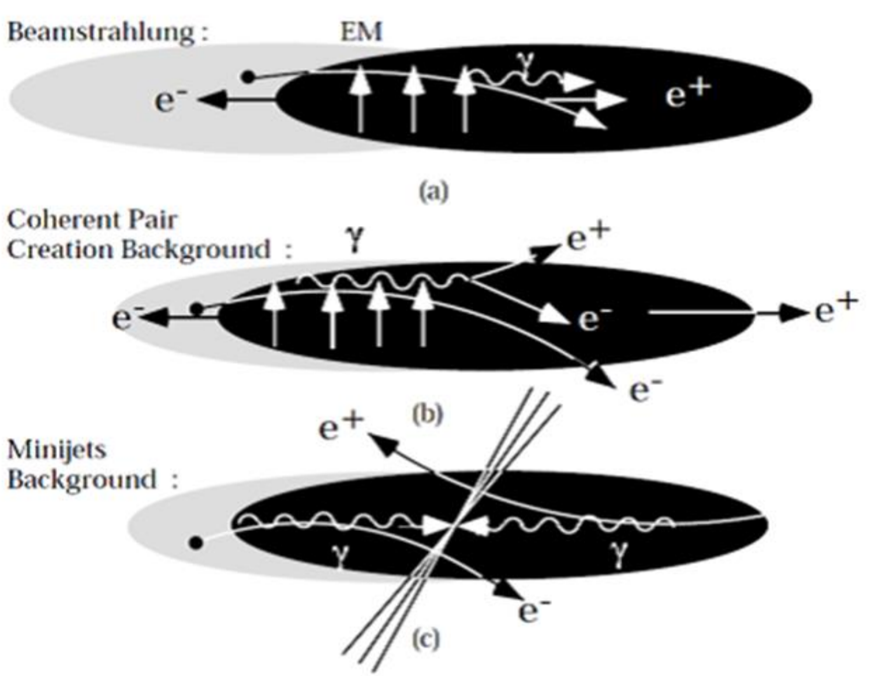
Υ 'Upsilon' parameter determines the ratio of the energy loss due to 'beamstrahlung' to the average particle energy in collision.

δ_B 'Delta B' parameter is the average energy loss of a beam particle to 'beamstrahlung'.

n_γ Finally, 'N-gamma' is the QCD hadronic background in terms of the hadronic cross-section. TYPICALLY: keep 'Upsilon' <0.3

$$\Upsilon >> 0.3$$
$$\delta_B > 0.1$$
$$n_\gamma >> 1 \; .$$

$$\Upsilon = \frac{0.43 r_e^2}{\alpha}\left(\frac{\gamma N}{\sigma_z \sigma_y^*}\right)\left(\frac{2}{1+R}\right) .$$



Scaled Natural Variables

$$\beta^*_{x,y} = \sigma_z \ \hat{\beta}_{x,y}$$

$$\sigma_z = (\lambda / 100) \ \hat{\sigma}_z$$

$$\gamma = 5x10^6 \ \hat{\gamma}$$

$$L = \left(10^{35} \mathrm{cm}^{-2} \mathrm{s}^{-1}\right) \hat{L}$$

$$\varepsilon_{N,x,y} = \left(10^{-6} \mathrm{mrad}\right) \hat{\varepsilon}_{N,x,y}$$

$$R = \left(\sigma^*_x / \sigma^*_y\right)$$

$$\lambda(\mathrm{cm}) = \left(\hat{\gamma} / \hat{\sigma}_z\right) \hat{\lambda} \ .$$

$$N \sim 10^8 \left(\hat{\varepsilon}_x \hat{\beta}_x\right)^{1/2} \left(\frac{1+R}{R}\right) \hat{\lambda}^{3/2} \Upsilon$$

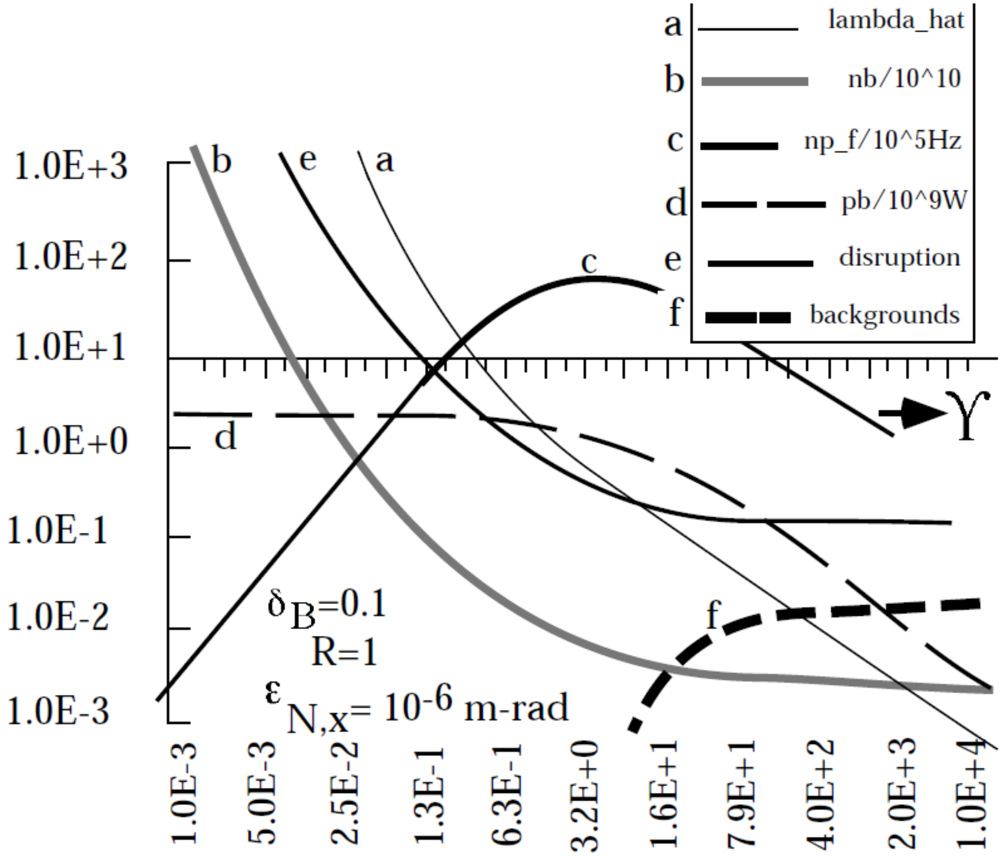
$$\delta_B \sim 0.5 \frac{\hat{\lambda} \Upsilon^2}{\left[1 + (1.5\Upsilon)^{2/3}\right]^2}$$

$$f \sim 2.6x10^7 \frac{R}{(1+R)^2} \frac{1}{\hat{\lambda}^2} \frac{1}{\Upsilon^2} \hat{L}$$

$$P_b \sim 2x10^9 \ \frac{\hat{\gamma} \ \hat{L}}{(1+R)} \ \frac{1}{\Upsilon} \ \frac{1}{\hat{\lambda}^{1/2}} \left(\hat{\varepsilon}_x \hat{\beta}_x\right)^{1/2}$$

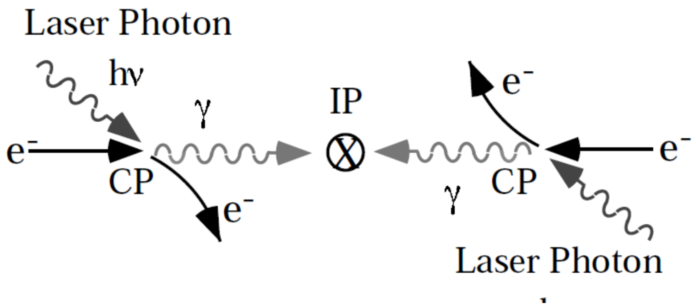
$$D_Y \sim 0.6 \ \Upsilon \ R \hat{\lambda}^{3/2} \left(\hat{\varepsilon}_x \hat{\beta}_x\right)^{-1/2} \ .$$

Scaling of 'scaled' variables as a function of 'Upsilon' beamstrahlung parameter for a 5 TeV c.m. electron-positron collider at a luminosity: L = 10 E 35 cm-2 s-1 (round beams, horizontal normalized emittance 10 E -6 m-rad, beamstrahlung energy spread, 'Delta B' ~10%

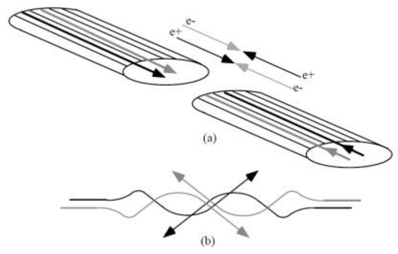


Moving away from Classical Scaling Paradigm

A. Photon-Photon Collisions.



B. Neutralized Beams



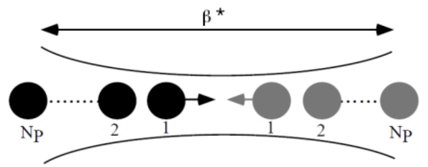
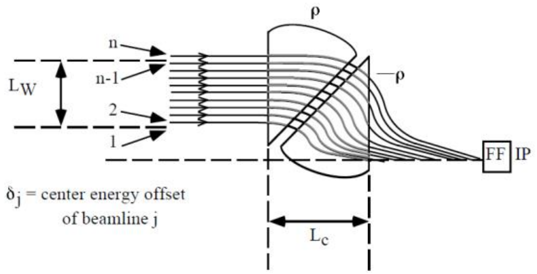


Figure 6



Requires very difficult manipulations: many bunches within Focal length "low beta*", beam combining and manipulating opposing charged beams in both channels

C. Other Options ***Requires very difficult 'Plasma Lens' compensation***

D. Accept Large Υ and δ_B

CURRENT STATUS OF 5 TeV LINEAR COLLIDER ULTIMATE LIMITS

Technology	*Wave-length λ*	*Potential Gradient*	*Collider Length*	*R & D*	*Technology Details*
SCRF	>10 cm	100 MV/m	60 km	Superconducting materials research; new superconductor; site	'Bismuthate' materials
RF	1 cm	200 MV/m	30 km	Power sources prototype, drive beam dynamics, site	**CLIC-like Two-beam Accelerator or normal RF at S-band, X-band etc.**
				sheet beam klystron research, site	30 GHz Tube Driven
mm-wave and THz	<3 mm	1 GV/m	< 10 km	pwr source invention, structure invention, fabrication tech.	90 GHz Dielectric 90 GHz Conducting 1 THz
Lasers & beams in plasmas & structures	<300 μm	>10 GV/m	~ km	module prototype, rep. rating guiding, staging, beam dynamics	laser structure-based laser plasma-based beam structure-based beam plasma-based
γγ	relevant to all the above			~10 kHz rep. rate, TW peak power lasers, IR mechanical configuration	

EVOLUTIUON PATH OF SCRF DIRECTION

Active Length	*Gradient*	*Material*	T_c	E_{max}	*CM Energy*	*Luminosity*
km	MV/m		°K	MV/m	GeV	$cm^{-2}s^{-1}$
20	25	Nb	9.2	60	500	$5x10^{33}$
20	40	Nb	9.2	60	800	10^{34}
40	40	Nb	9.2	60	1600	$2x10^{34}$
40	80	Nb_3Sn	18	100	3200	$6x10^{34}$
40	120	$BaKBi0_3$	30	160?	4800	10^{35}

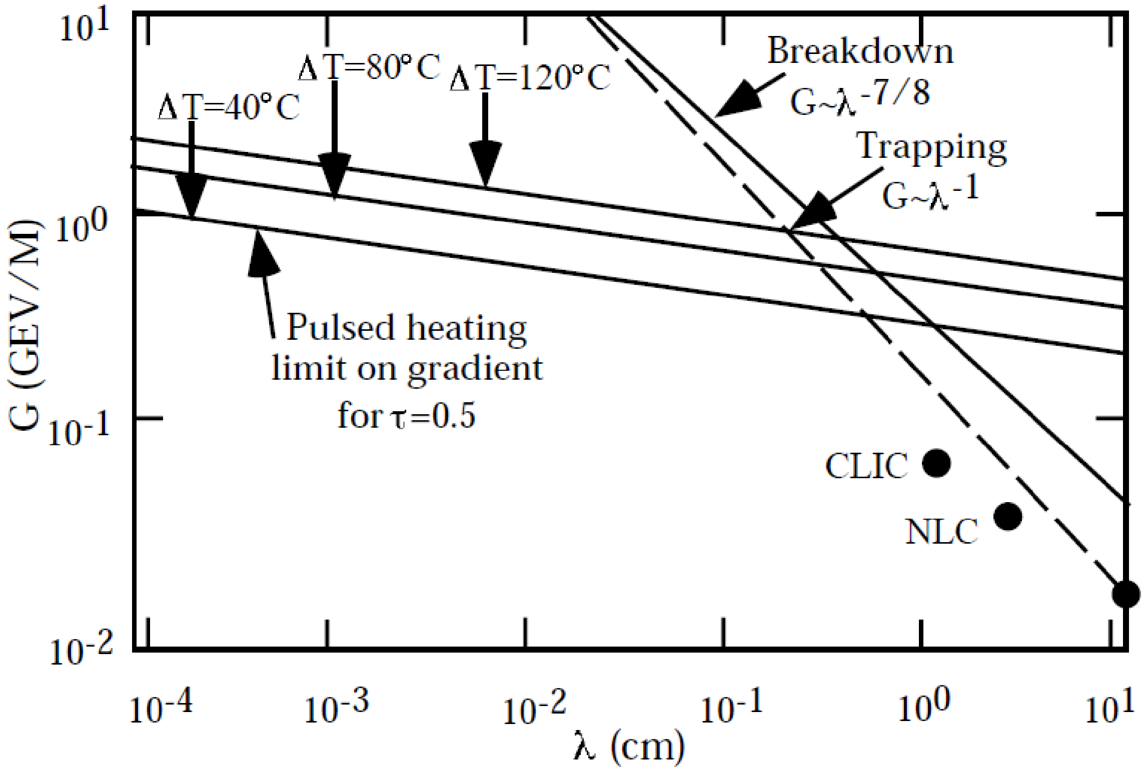
ULTIMATE BEAM for a SUPERCONDUCTING RF-BASED 5 TeV LINEAR COLLIDER

$L \sim 10^{35} cm^{-2} s^{-1}$	$N \sim 2.7 \times 10^{10}$
$f \sim 4.7$ kHz	$N_P \sim 20{,}000$
Spot Size :	1.3 nm x 505 nm
Normalized Emittance :	10^{-8} m-rad x 10^{-8} m-rad
$\Upsilon \sim 2.3$	$\delta_B \sim 23\%$

EVOLUTIUON PATH OF NORMAL CONDUCTING RF

GRADIENT LIMITS OF METALLIC ACCELERATING STRUCTURES DUE TO 'PULSED HEATING'

$$G_{PH} \sim 0.3\left(\frac{GV}{m}\right)\left[\frac{\Delta T}{50^\circ C}\right]^{1/2} \lambda_{(cm.)}^{-1/8} \tau^{-1/4}\left[\frac{\sigma K C}{(\sigma K C)_{Cu}}\right]^{1/4} \quad (11)$$



ULTIMATE BEAM for a NORMAL COINDUCTING RF-BASED 5 TeV LINEAR COLLIDER

$L \sim 10^{35}\ cm^{-2}s^{-1}$	$N \sim 2.4 \times 10^{9}$
$f \sim 120$ Hz	$N_p \sim 225$
Spot Size :	0.5 nm x 40 nm
Normalized Emittance :	10^{-8} m-rad x 10^{-6} m-rad
$\Upsilon \sim 2.7$	$\delta_B \sim 27\%$

IT IS PREMATURE TO SPECULATE ULTIMATE BEAM for LASER-PLASMA or BEAM-PLASMA WAKEFIELD-BASED LINEAR COLLIDER UNTIL R&D HAS PROGRESSED FOR ANOTHER DECADE

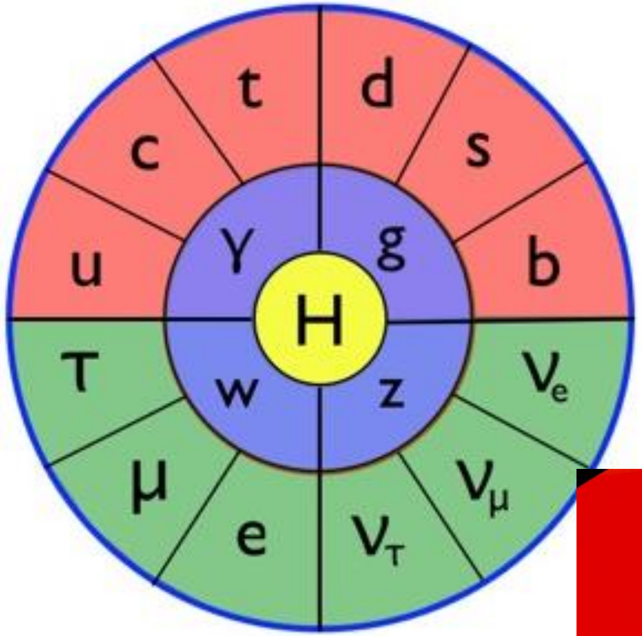
“Radiative Regime of Linear Colliders, High Repetition Rate Free Electron Lasers and Associated Accelerating Structures”, Swapan Chattopadhyay and Roger Jones*,* ***Nucl. Instrum. Meth.***
***A* 657 (2011) 168-176**

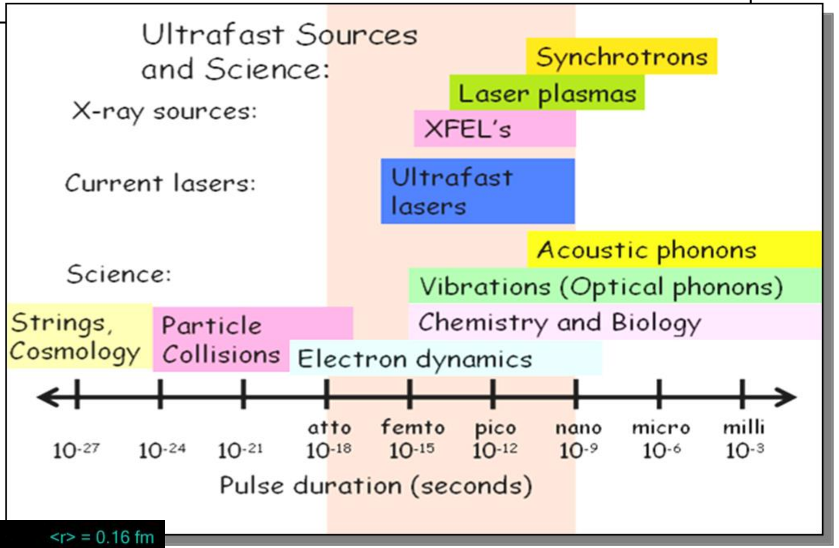
“Advanced Accelerating Technologies: A Snowmass’96 Subgroup Summary”, Swapan Chattopadhyay, David Whittum and Jonathan Wurtele, **Proceedings of the 1996 DPF/DPB Summer Study on New Directions for High-Energy Physics (Snowmass ‘96), SLAC-PUB-9914**

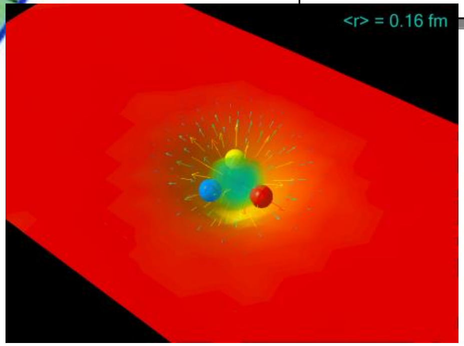
A large number of dedicated particle physics experimentalists, theorists and accelerator scientists, have now developed what I will call

The Standard Model Mandala

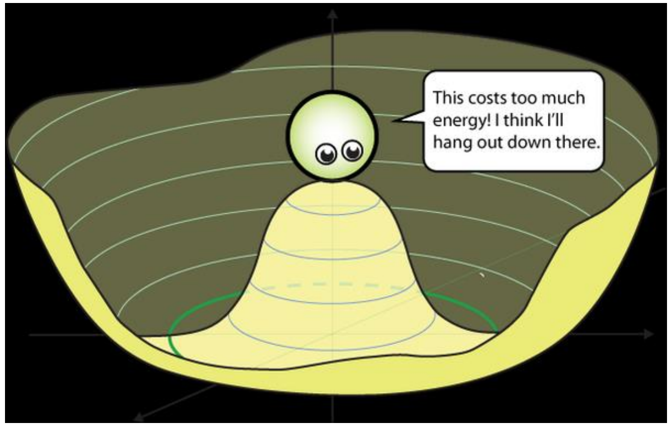
Latest Discovery: Higgs particle!!

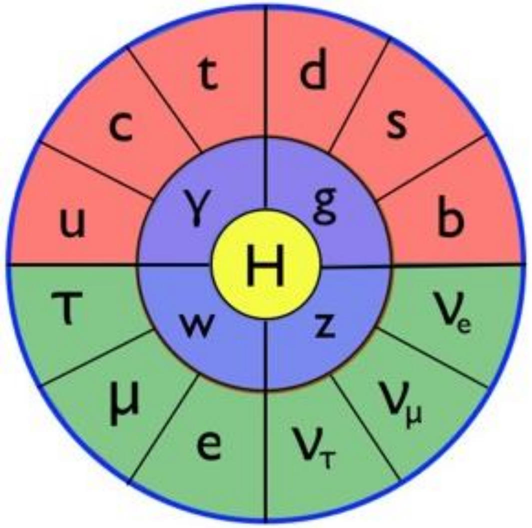


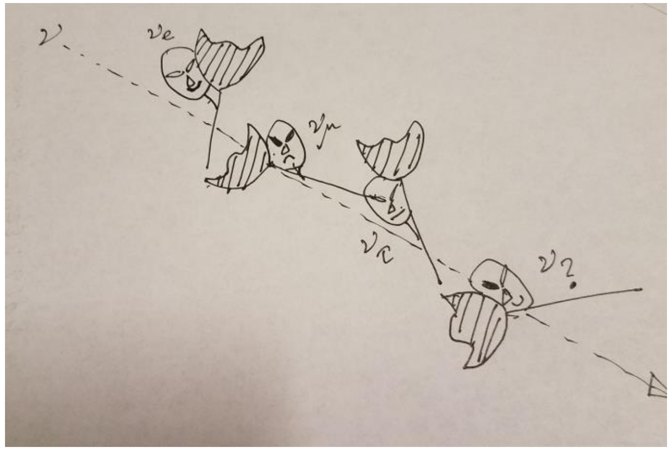




The Standard Model Mandala: Least understood: "mysterious" Higgs and "elusive" Neutrinos







To advance understanding of Higgs, need even higher energy colliders than available today:

→ **FCC (CERN plan or elsewhere), ILC/CLIC,..**

To advance understanding of Neutrinos, need higher power proton accelerators for long-baseline Neutrino experiments:

→ **Y2K (Japan) and DUNE/PIP-II (US)**

But while *Higgs* and *Neutrinos* are to complete the Standard Model, they are only a small part of Nature's canvas…

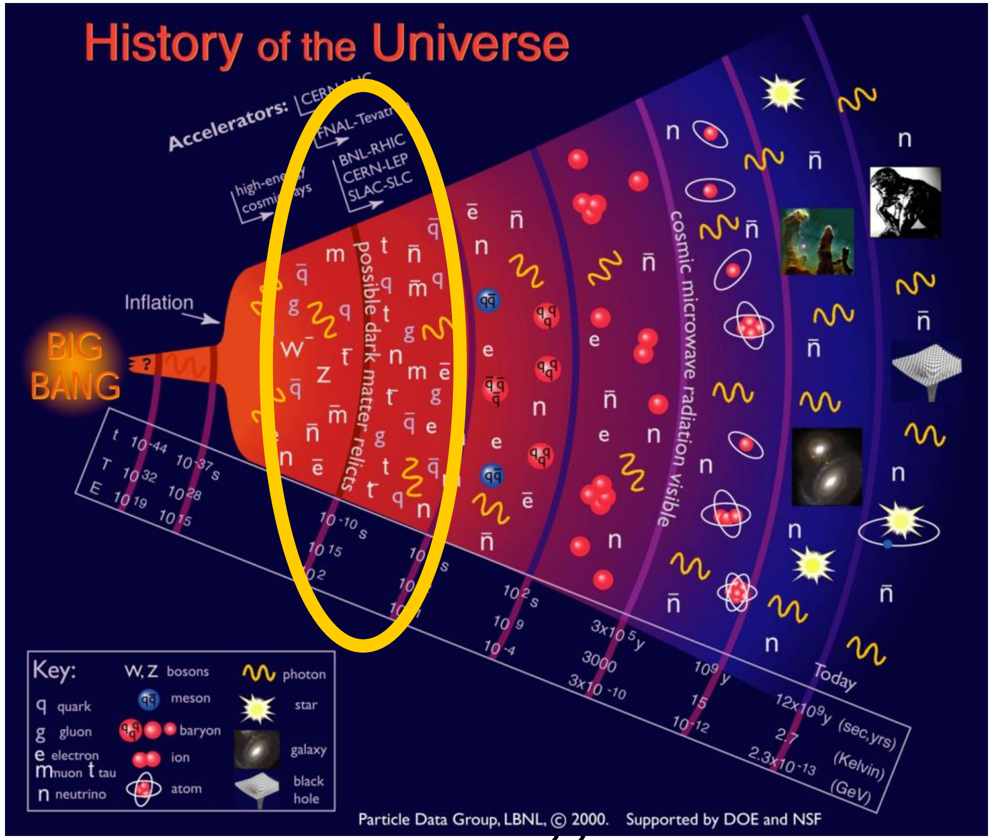
→ *"Early" and "Dark" Universe, Symmetries, Quantum Gravity*

1. ***Dark Matter***
2. ***Dark Energy***
3. ***Cosmic Gravitational Background radiation***
4. ***Inflation***
5. ***Must 'Gravity' conform to a Gauge Field (Gravitons?)***
6. ***Quantum Gravity?***
7. ***Space-time Symmetries --- foundation rock of the Standard Model – has no meaning when gravitation and cosmological scales are considered. Should we expect violation of Lorentz Invariance? …..etc. etc. ……….***

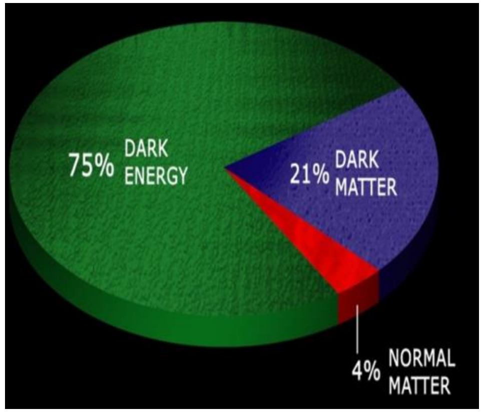
Telescopes to the early universe

Reaching the energy scale in the laboratory to simulate the earlier times and higher energies in the Universe's evolution is daunting! But, the "signals" are all there in the space-time of our laboratories, albeit as very weak "tremors" and "fossils" from the Big-Bang early universe! Need "Cosmic Archaeology"!

Big Bang



now



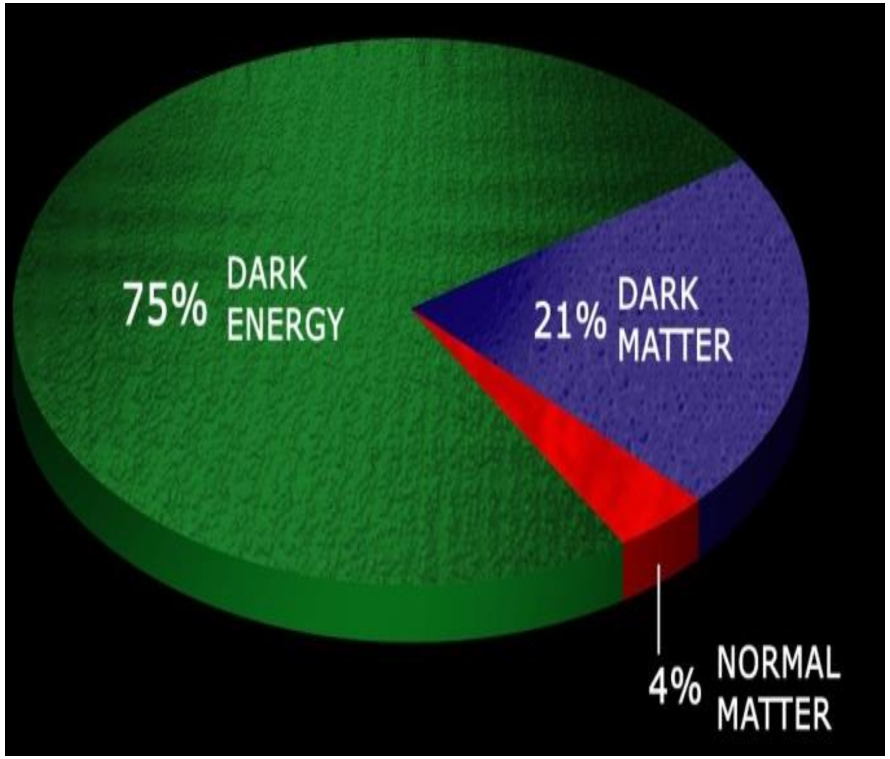
Universe was already "entangled" at the Planck-scale. There was a single wavefunction of the universe at the Planck –scale: Ψ_{Planck}

$$H_A \otimes H_B. \rightarrow |\psi\rangle_A \otimes |\phi\rangle_B.$$

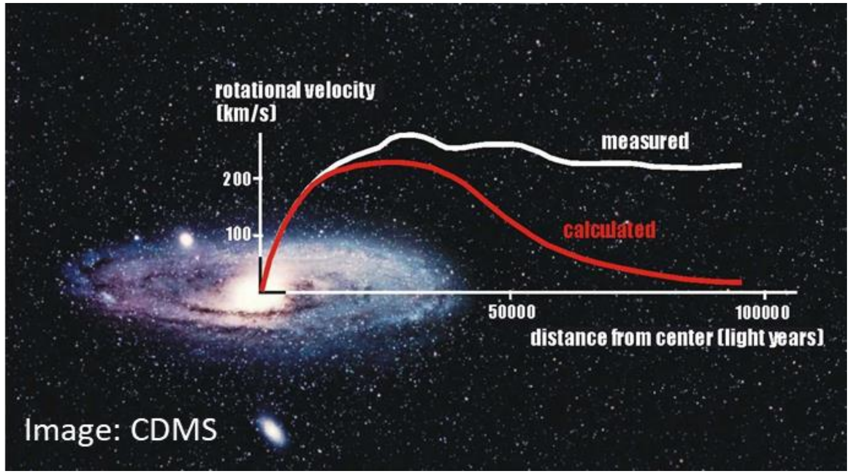
$$\Psi_{\text{Planck}} \rightarrow \Psi_{\text{A}} \otimes \Psi_{\text{B}}$$

$$|\psi\rangle_{AB} = \sum_{i,j} c_{ij} |i\rangle_A \otimes |j\rangle_B$$

TWO major areas begging exploration beyond the Standard Model of Particle Physics: the "Dark Matter" and the "Dark Energy": Quantum Sensors are unique as probes of the "Dark" sector



$$\frac{\dot{a}^2}{a^2} = \frac{8\pi G}{3}\rho - \frac{kc^2}{a^2} + \frac{\Lambda}{3}$$



Today's Measure of the Mass-Energy Budget of the Universe

PHYSICAL MEASURE of the DARK SECTOR:
DARK MATTER/ENERGY and FORCE ESTIMATES

$$\Omega_{DE} \quad = \quad 6.3\times10^{-10}\ \mathrm{Jm}^{-3}$$

Corresponds to energy density of a static electric field:

$E = 12$ V/m (Dark Energy)

"Dark Matter" density is even higher implying:

Ω_{DM} $E \sim 10$ kV/m !! (Dark Matter)

Must look for "AC"-effects (fluctuations) on a fixed background!

~ 4×10^{-10} Nm^{-2} → Measurement of Casimir effect (1996)

~ 1.3×10^{-10} Nm^{-2} → Cold cathode ionization gauge

The Problem of Dark Matter

Fit in visible galaxy

One Possibility: Same scale as visible galaxy for Dark Matter?

Dark Sun, Other Dark Stars, Dark Milky Way Galaxy,..??

Many Generic Conceptual/Theoretical Candidates:

Hidden Sector Photons, Axions, Massive Vector Bosons, Relaxions, ….

How do we search for them? → AC Effects of Dark Matter:

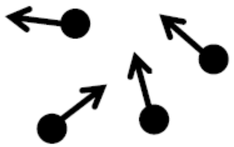
I. On Photons ***(Sensitive and Precise Coupling to "alpha"~ 1/137)*** *****

II. On Electrons/Nucleons ***(SQUIDS : Materials with Special NMR properties)***

****** I will only discuss this technique***

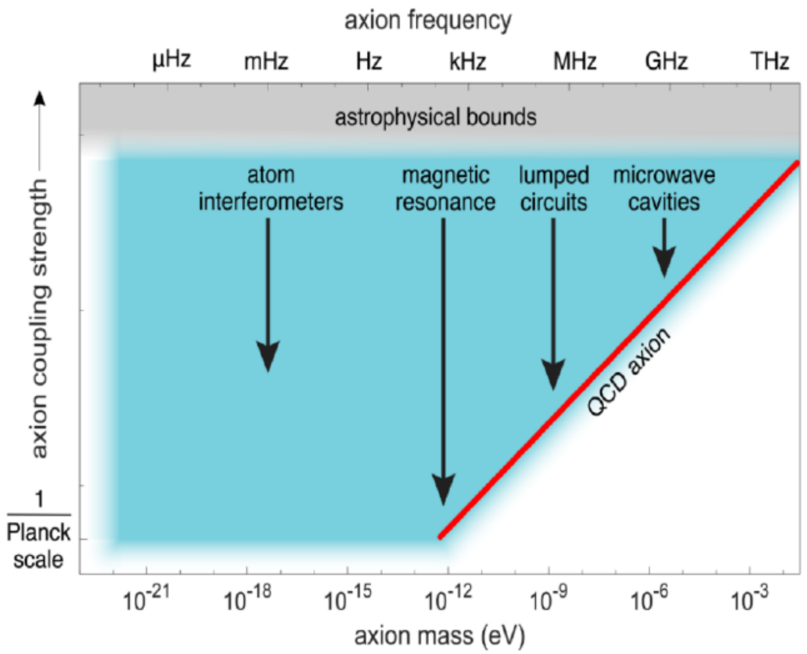
Ultralight dark matter

WIMPS
- Mass ~10 GeV (10x proton)
- Particle-like (deposit energy in detector)



"Ultralight" dark matter (e.g., axions, dilatons, etc.)
- Low mass, high number density
- Would act like a **classical field**

One example is the axion, and axion-like particles:



Dark matter BRN report

Emerging Quantum Initiatives:

Quantum Sensors
invoking
'Quantum Entanglement'
and
'Quantum Superposition'

QUANTUM SENSORS - *Mais, qu'est-ce que c'est?*

Quantum Sensors – *i.e. instruments that exploit quantum physics in general and the fundamental phenomenon of "quantum entanglement" in natural systems in particular --* have the potential of enabling "precision-" and "discovery-class" research in Fundamental Science, Quantum Information Science and Computing.

Ordinary Quantum Limits in Impulse Sensing

Standard quantum limit for momentum transfer:

$$\Delta p_{SQL} = \sqrt{\hbar m_s \omega}$$

1.5 MeV (m = 1 ng, ω = 1 kHz)

1.5 μeV (m = 1 m_e, ω = 1 kHz)

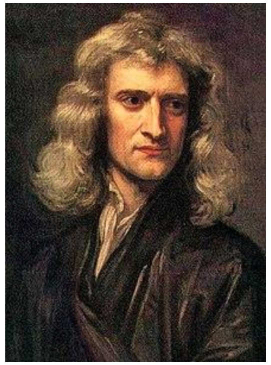
Again this is just a benchmark. “Simple” and natural ways to go below this level:

- **Beat the Zero-point noise**
- **Squeezing, Non-demolition/back-action evasion**
- **State transport and transduction**
- **Single photon detectors**
- **Measuring arbitrarily small forces**
- **Cooper pair-breaking detectors**

WHY Invoke Quantum Entanglement?

Quantum Entanglement allows for "Squeezed" states and approach the quantum limit of a single photon

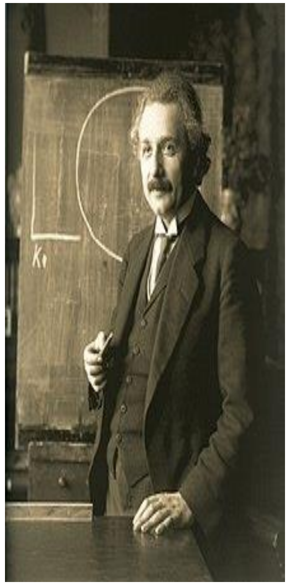
Why so? QUANTUM ENTANGLEMENT ALLOWS for "SQUEEZED" STATES

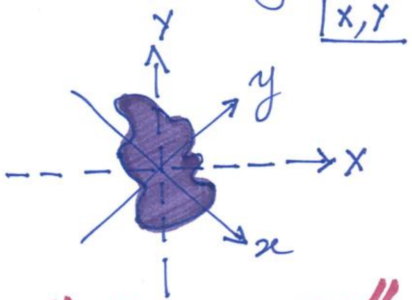


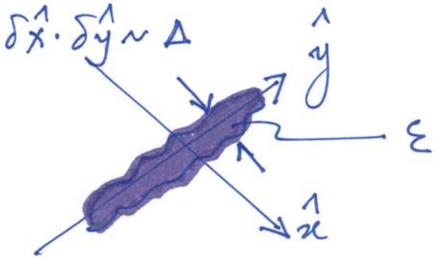
"ENTANGLED" $(x \wedge y)$

"INDEPENDENT" (x, y)

Allows for "squeezing" information content in 'x' to narrowly constrained values at the cost of "scattering" back and depositing non-essential information into "y"



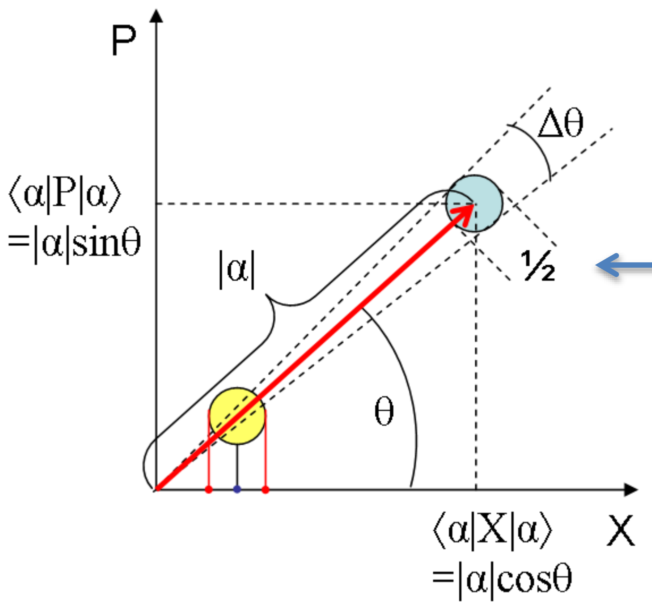




Quantum "state-space" allows for "SQUEEZED" STATES.

$\delta\hat{x} < \varepsilon$, non-essential information in $\delta\hat{y} > \Delta/\varepsilon$

EXAMPLE: Low Level Detection of Radio-Frequency Waves: Quantum-limited amplifiers suffer from zero-point noise



½ ħ= quantum of phase space area.
Simultaneous measurement of wave amplitude and phase gives irreducible zero-point noise in measurement.
(Caves, 1982)

Thermal noise = ½ kT per resolved mode
→ Quantum noise = 1 photon per resolved mode in the T=0 limit.

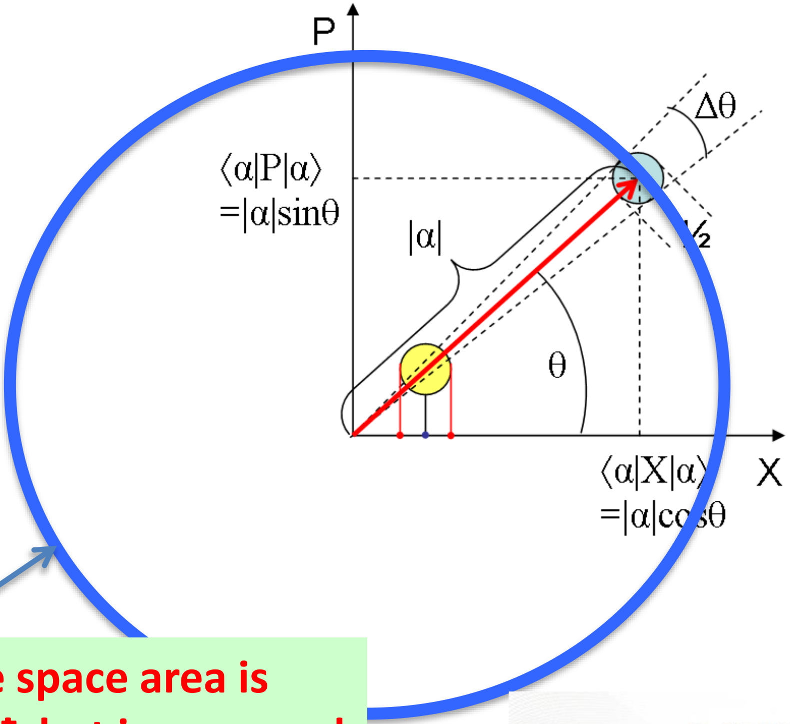
Noise photon rate exceeds signal rate in many high frequency high precision signal detection schemes for exotic searches of very "weak" processes..

Need new sensor technology….

Quantum Non-Demolition (QND) single photon counting technique can do much better : Probing cavity photon number exactly without absorbing/destroying any photon

Number operator commutes with the Hamiltonian→ all back reaction is put into the phase.
Noise = shot noise, thermal backgrounds.

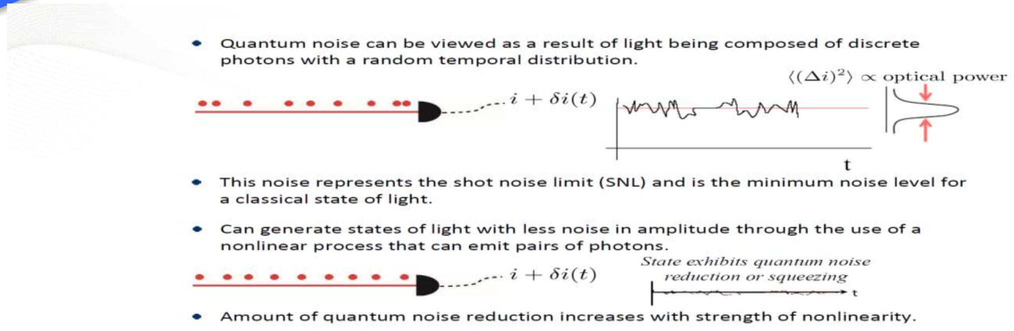
4 orders of magnitude improvement in sensitivity for probing "ultra-weak" processes!



Demonstrated with Rydberg atoms, (Haroche/Wineland Nobel Prize 2012)
Implemented as solid state qubits for quantum computing, (Schoelkopf/ Schuster, 2007)

At T<30 mK, 10 GHz, Boltzmann-suppressed thermal blackbody photon background rate is 10^{-4} of zero-point noise.

Phase space area is still ½ħ but is squeezed in radial (amplitude) direction. Phase of wave is randomized.

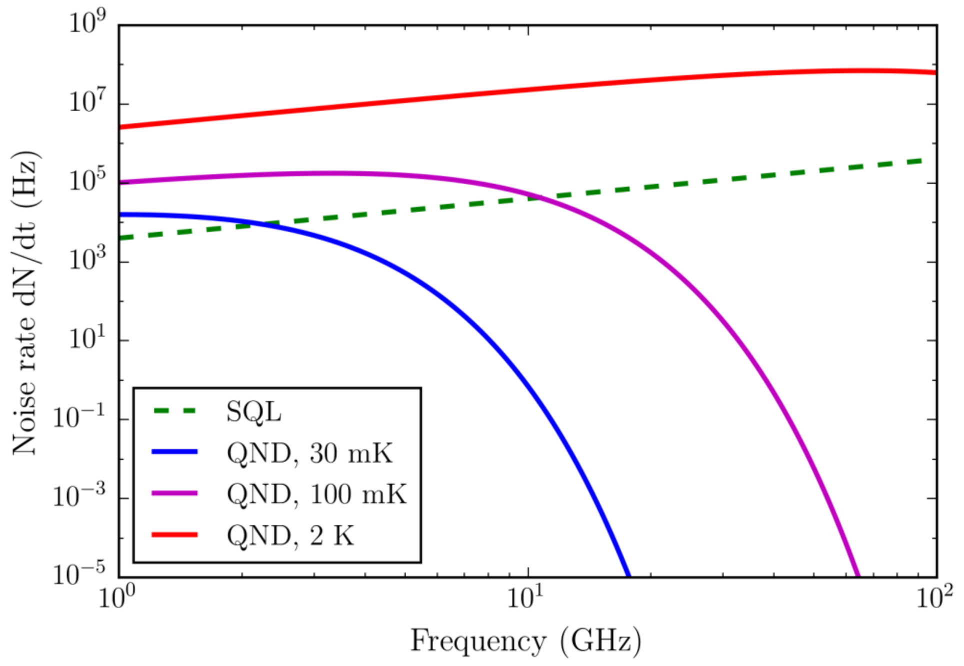


- Quantum noise can be viewed as a result of light being composed of discrete photons with a random temporal distribution.

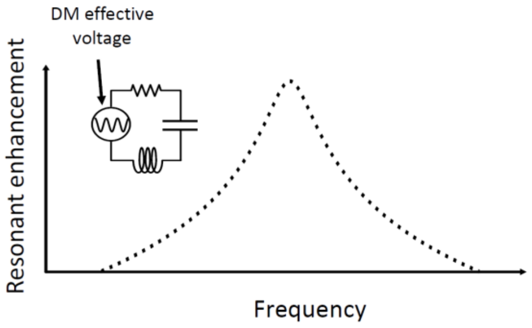
- This noise represents the shot noise limit (SNL) and is the minimum noise level for a classical state of light.
- Can generate states of light with less noise in amplitude through the use of a nonlinear process that can emit pairs of photons.

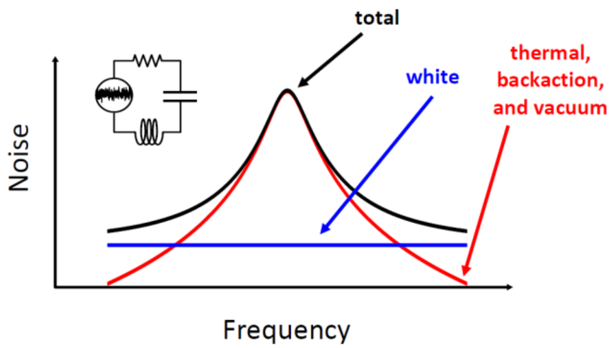
- Amount of quantum noise reduction increases with strength of nonlinearity.

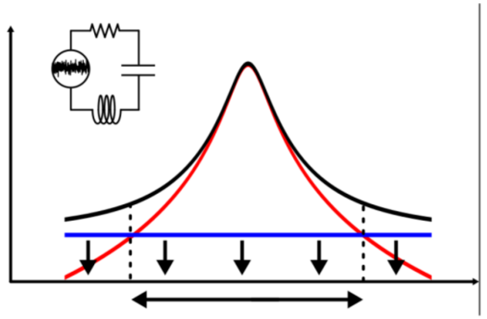
Noise rates, qubits vs quantum-limited amplifiers



Linear amplifiers suffer from the "standard quantum limit" (SQL, Caves, 1980): 1 photon's worth of noise per frequency-resolved mode. Quantum Non-Demolition (QND) measurements' noise is blackbody-dominant. Cooling to O(10) mK gives clear benefits.







SC Cavity- SC Qubit Electrodynamics to probe for "dark" sector particles:
Axions, Hidden Sector Photons
→ ***REORIENT SUPERCONDUCTING CAVITY and MAGNET FRONTIER***

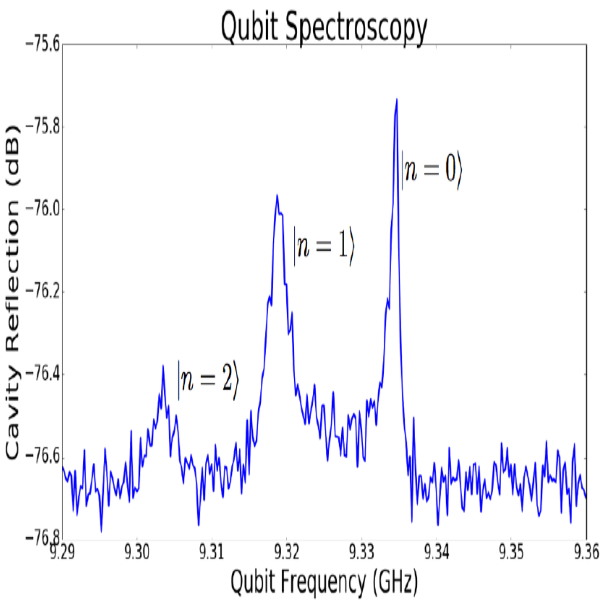
Atom Interferometry: : Early and Dark Universe, Cosmic Gravitational wave backgrounds,…
→ Reorient Laser, Atomic Beams and Ultra-High Vacuum technologies

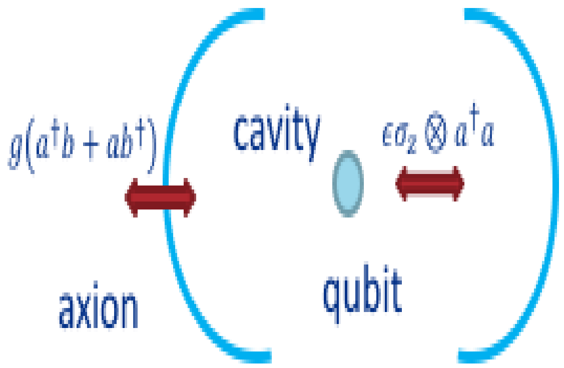
Quantum-entangled materials (Dirac and Weyl, Nitrogen Vacancy Diamond, specially designed NMR materials) for Precision Detection:
Exotic particles, …
→ GOING BEYOND SILICON DETECTORS

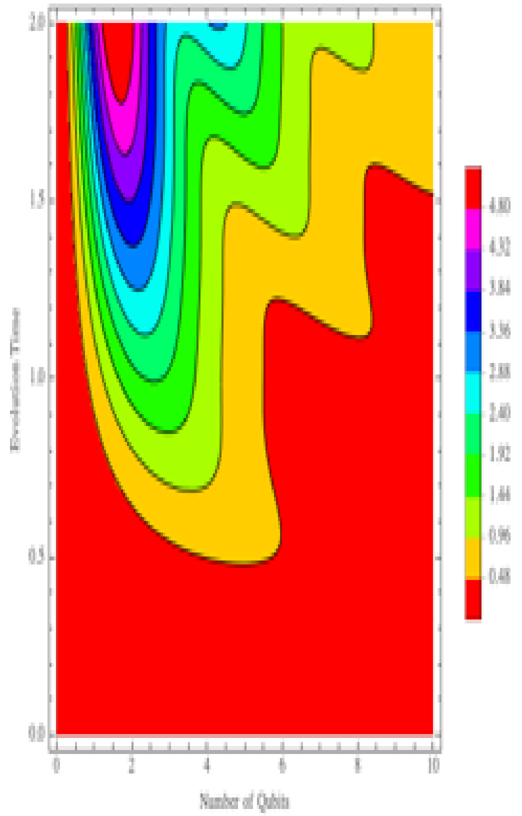
Accelerators Beyond Colliders: → Fixed Target High Intensity Accelerators for "Darkstrahlung"

Advanced Lasers: : Space-time Symmetries, Lorentz Invariance,…
→ REORIENT LASER DEVELOPMENT

Qubit-based single microwave photon sensors for Dark Matter Detection







Contour Plot for Fisher Information given $(\alpha|0\rangle^{\otimes n} + \beta|1\rangle^{\otimes n})|1,0\rangle$

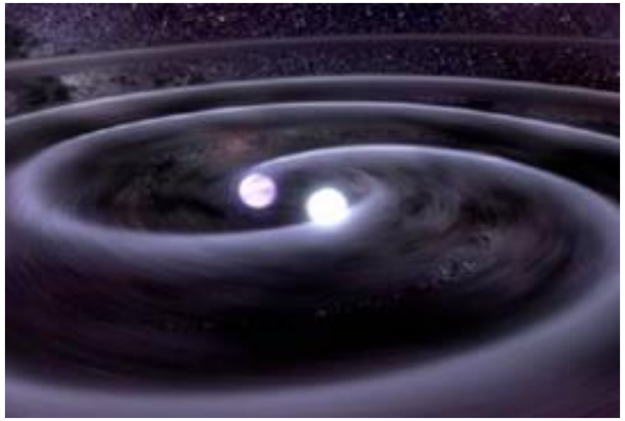
Probing the Very Early Universe and the "Dark" Universe:
via Atomic Beam Interferometry

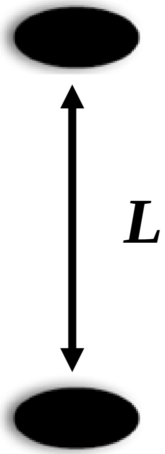
Detection of Stochastic Low Frequency Gravitational Wave Background from the "Inflationary" Era

+

Perturbed Atomic Transitions via Coupling of the Electromagnetic Sector (i.e. fine structure constant) with the "Dark" sector

GW detection with atoms





frequency

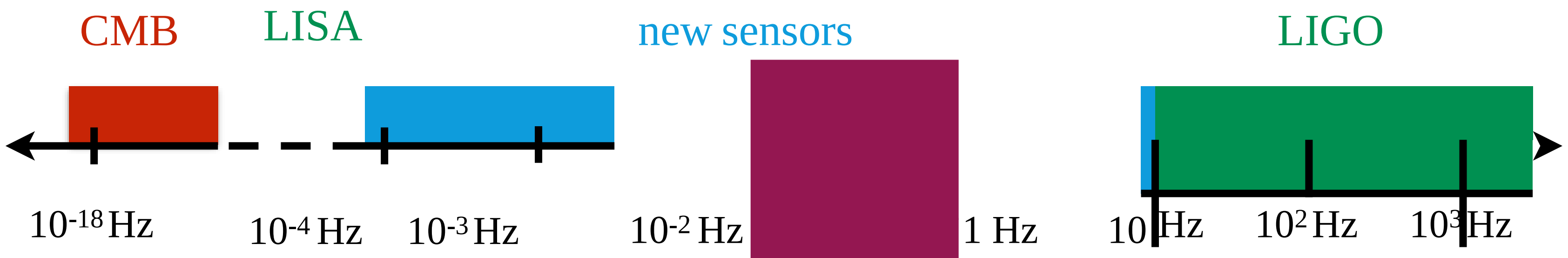
$$L\,(1 + h\,\sin(\omega t))$$

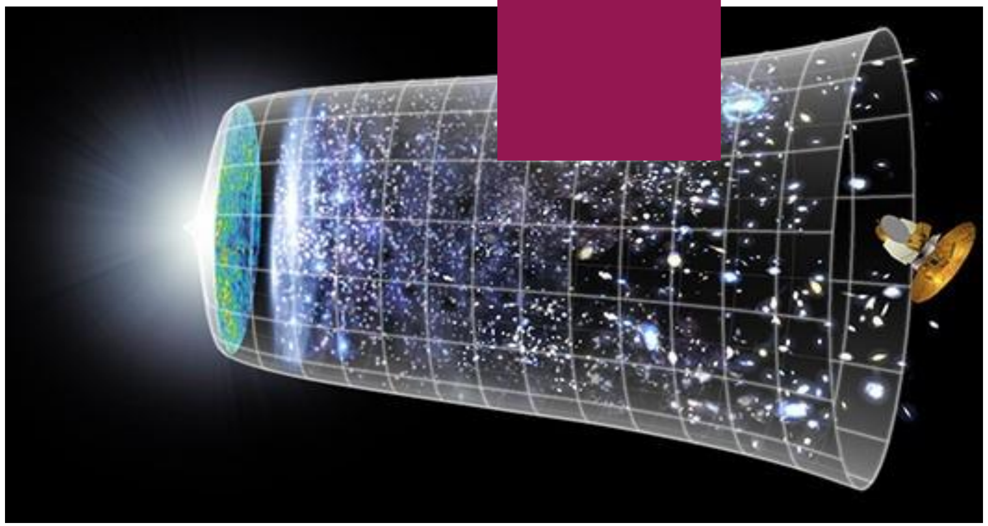
strain

Measure differential acceleration between two inertial masses

	LIGO	Atom Interferometry
Proof mass	Suspended end mirrors	Freely falling atoms
Proof mass separation	Laser interferometry	Light flight time
Reference	2nd interferometer arm	Atomic phase (clock)

Gravitational Wave Spectrum





"Atomic beam interferometer can bridge the gap -- the mid-band gap – between LIGO and LISA

Ultralight scalar dark matter

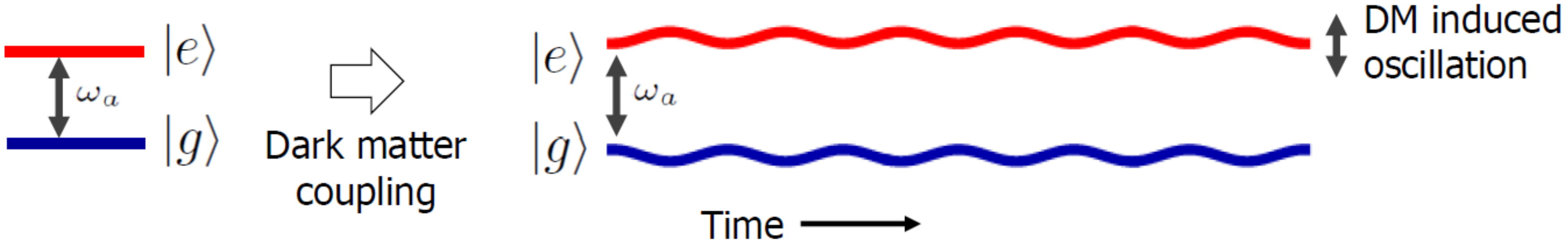
Ultralight dilaton DM acts as a background field (e.g., mass ~10^{-15} eV)

$$\mathcal{L} = \underbrace{+\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m_\phi^2\phi^2}_{\text{DM scalar field}} - \sqrt{4\pi G_N}\phi\left[\underbrace{d_{m_e} m_e\bar{e}e}_{\text{Electron coupling}} - \underbrace{\frac{d_e}{4}F_{\mu\nu}F^{\mu\nu}}_{\text{Photon coupling}}\right] + \underbrace{\ldots}_{\text{e.g., QCD}}$$

$$\phi\left(t,\mathbf{x}\right) = \phi_0\cos\left[m_\phi(t-\mathbf{v}\cdot\mathbf{x})+\beta\right] + \mathcal{O}\left(|\mathbf{v}|^2\right)$$

$\phi_0 \propto \sqrt{\rho_{\mathrm{DM}}}$ DM mass density

DM coupling causes time-varying atomic energy levels:

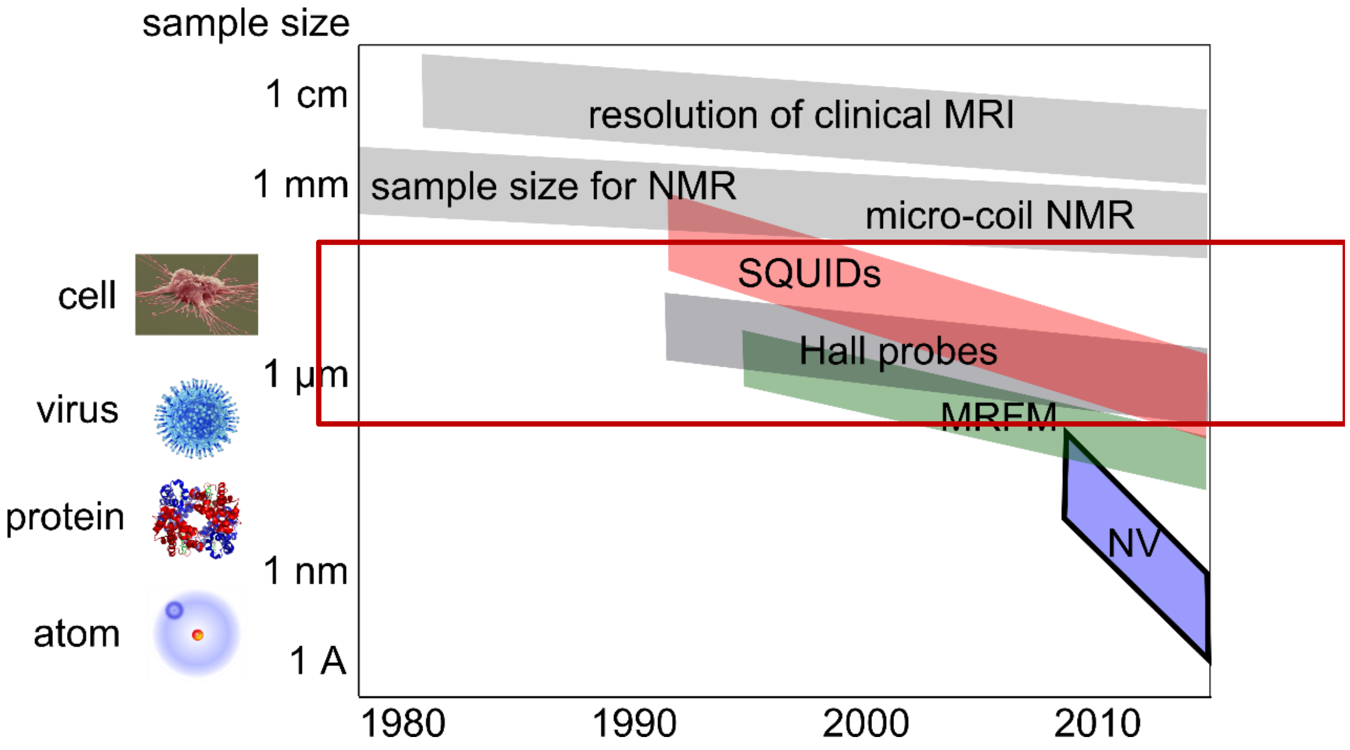


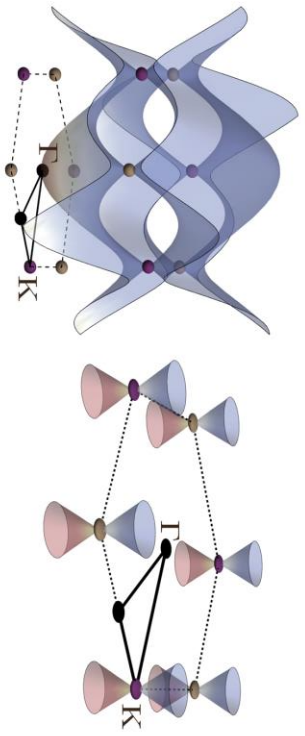
PROMISE of OTHER QUANTUM SENSORS:

→ Today's state-of-the-art Quantum Cavity Opto-mechanics operate in any part of the EM Spectrum from kilogram to femtogram scale from DC to 10 GHz

→ Trapped Ions, Cold Molecules, Cold Atoms, NV (Nitrogen-Vacancy) centres

→ 'Dirac' and 'Weyl' topological materials can couple ordinary matter to 'dark' matter by shrinking the 'band-gap' between valence and conduction bands



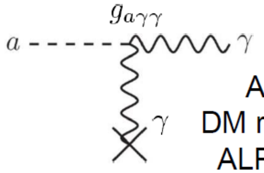


SPIN-BASED SEARCHES for ULTRALIGHT DARK MATTER and AXIONS

axion field amplitude → $\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}$

symmetry breaking scale

coupling to photons



ADMX, HAYSTAC,
DM radio, ABRA, SHAFT,
ALPS, CAST, IAXO, …

$\frac{a}{f_a} G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\frac{\partial_\mu a}{f_a}\bar{\Psi}_f \gamma^\mu \gamma_5 \Psi_f$
coupling to gluons	**coupling to fermions**
→ creates oscillating nucleon electric dipole moment (EDM)	→ creates axion "wind"
→ spin to axion coupling:	→ spin to axion "wind" coupling:
$H \propto \vec{\boldsymbol{d}} \cdot \vec{\boldsymbol{E}}_{eff}$	$H \propto \vec{\boldsymbol{\mu}} \cdot \vec{\boldsymbol{B}}_{eff}$

a figure of merit →

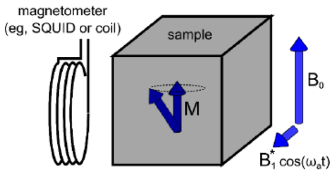
$$\xi = xp\sqrt{N\tau}$$

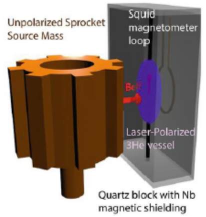
polarization

number of spins

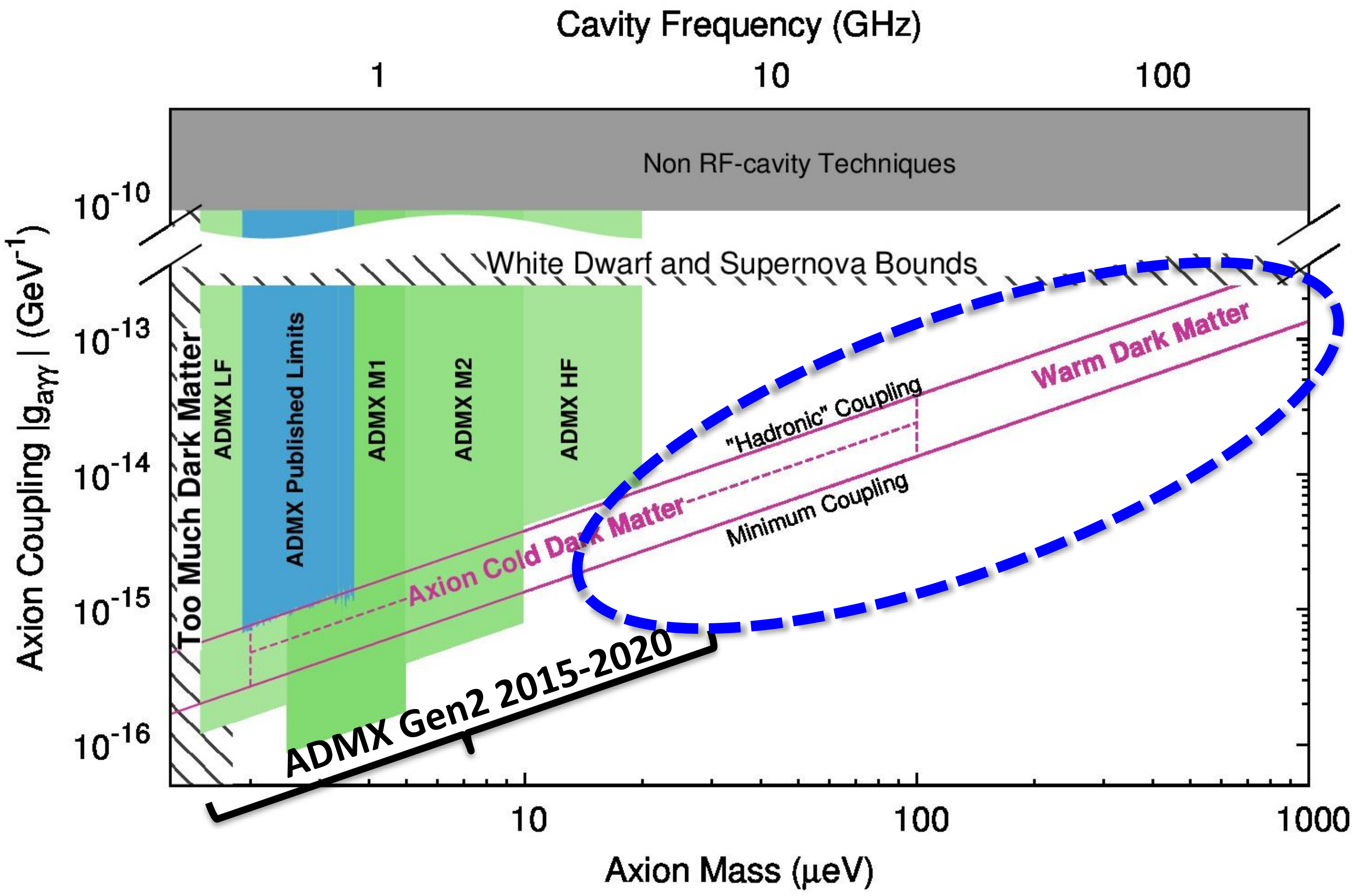
coherence time

- CASPEr collaboration: g_d, g_{an} [D. Budker et al., *Phys. Rev. X* **4**, 021030 (2014)] [A. Garcon et al., *Science Adv.* **5**, eaax4539 (2019)]
- QUAX collaboration: g_{ae} [N. Crescini et al., *Phys. Rev. Lett.* **124**, 171801 (2020)]
- ARIADNE collaboration: g_{an} [A. Arvanitaki and A. Geraci, *Phys. Rev. Lett.* **113**, 161801 (2014)]





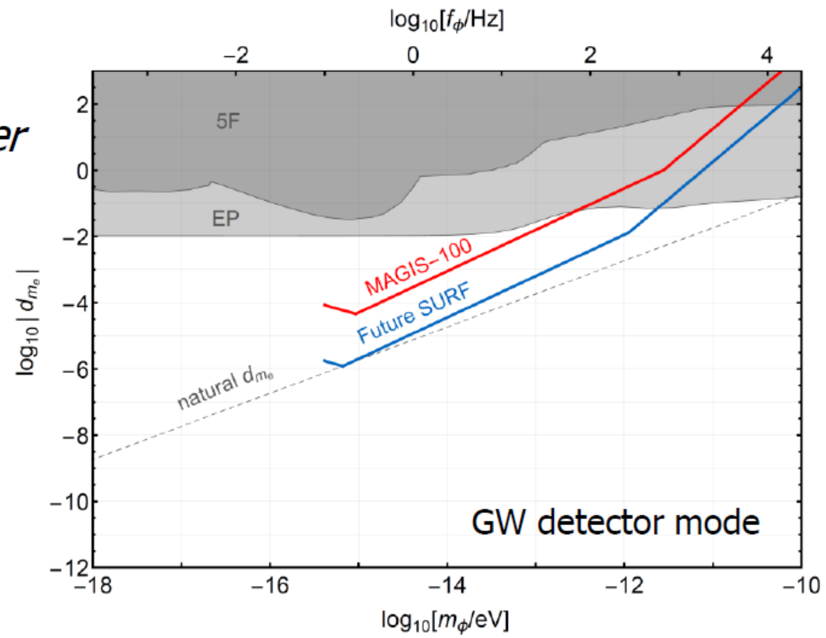
Qubit-based detectors enable coverage of remaining dark matter Axion parameter space – basis of Gen-3 ADMX experiment

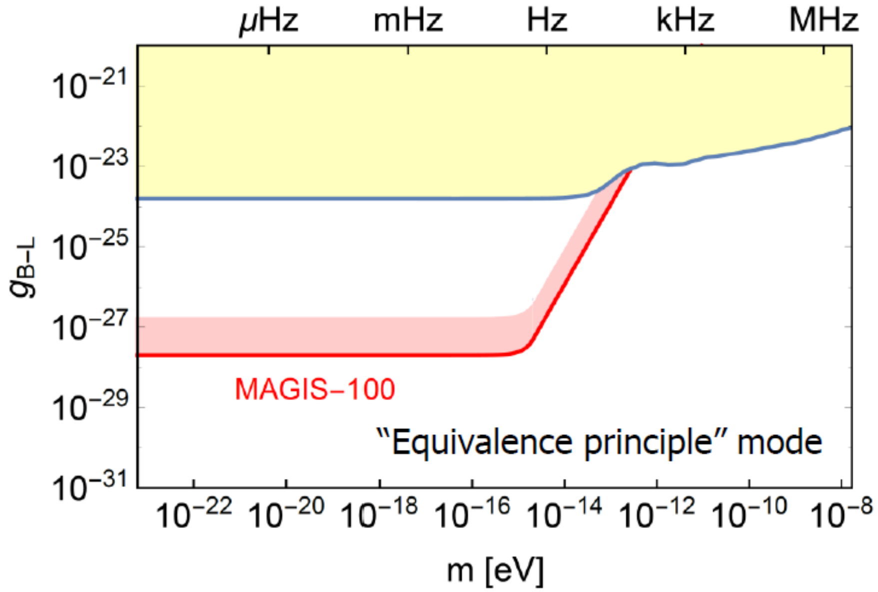


Lots of low hanging fruit for fundamental science applications in time frame of a decade as knowledge transfer before a practical quantum computer becomes practical in many decades!

Projected sensitivity to dark matter for MAGIS-100

Sensitivity to ultralight scalar dark matter





Sensitivity to B-L coupled new force ("fifth force" search)

~ 1 year data taking

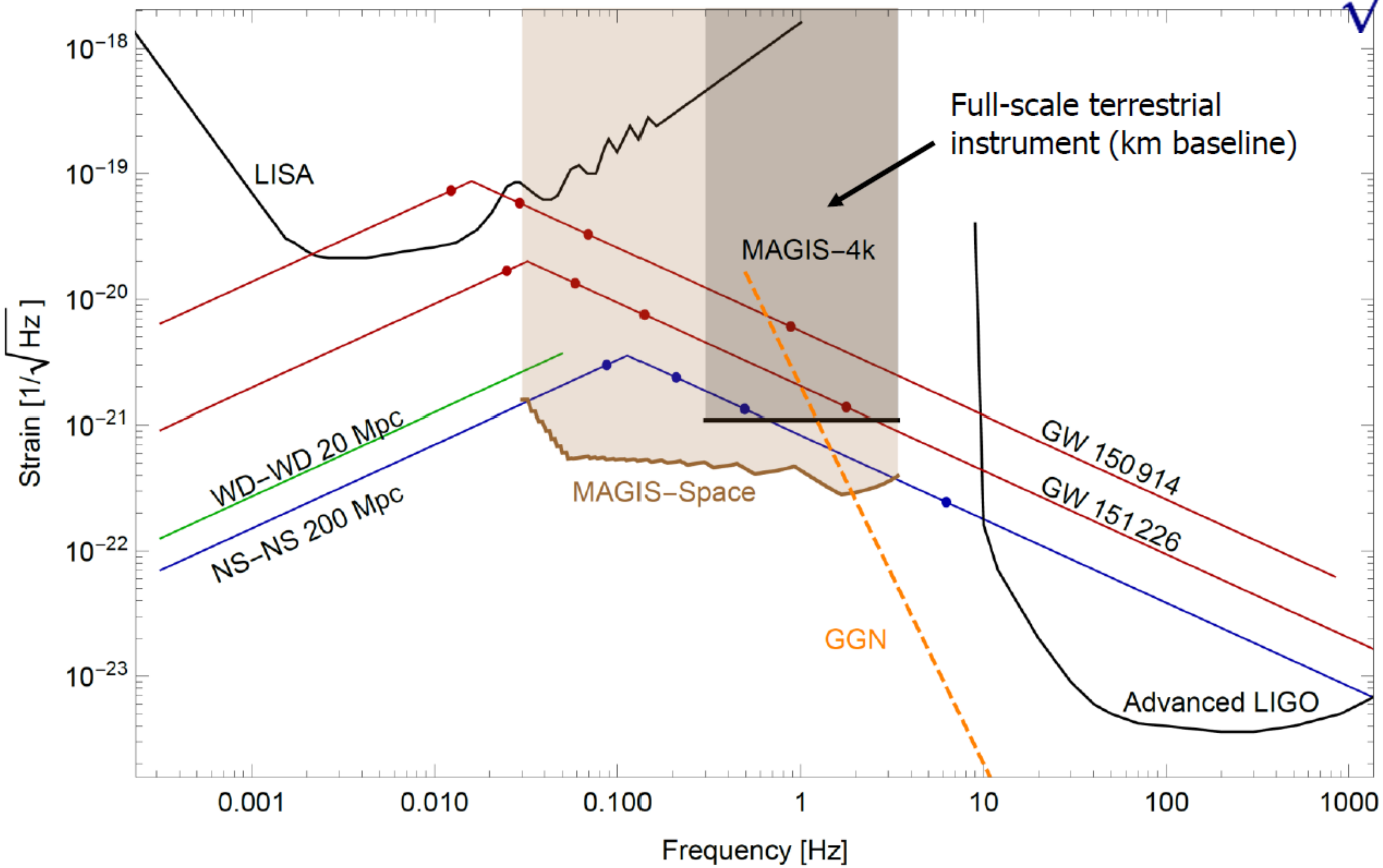
Assuming shot-noise limited phase resolution

Graham et al. PRD **93**, 075029 (2016).

Arvanitaki et al., PRD **97**, 075020 (2018).

Projected gravitational wave sensitivity

Accelerometers $\lesssim 10^{-13} \frac{\text{g}}{\sqrt{\text{Hz}}}$



Dots indicate remaining lifetimes of 10 years, 1 year, 0.1 years, and 0.01 years

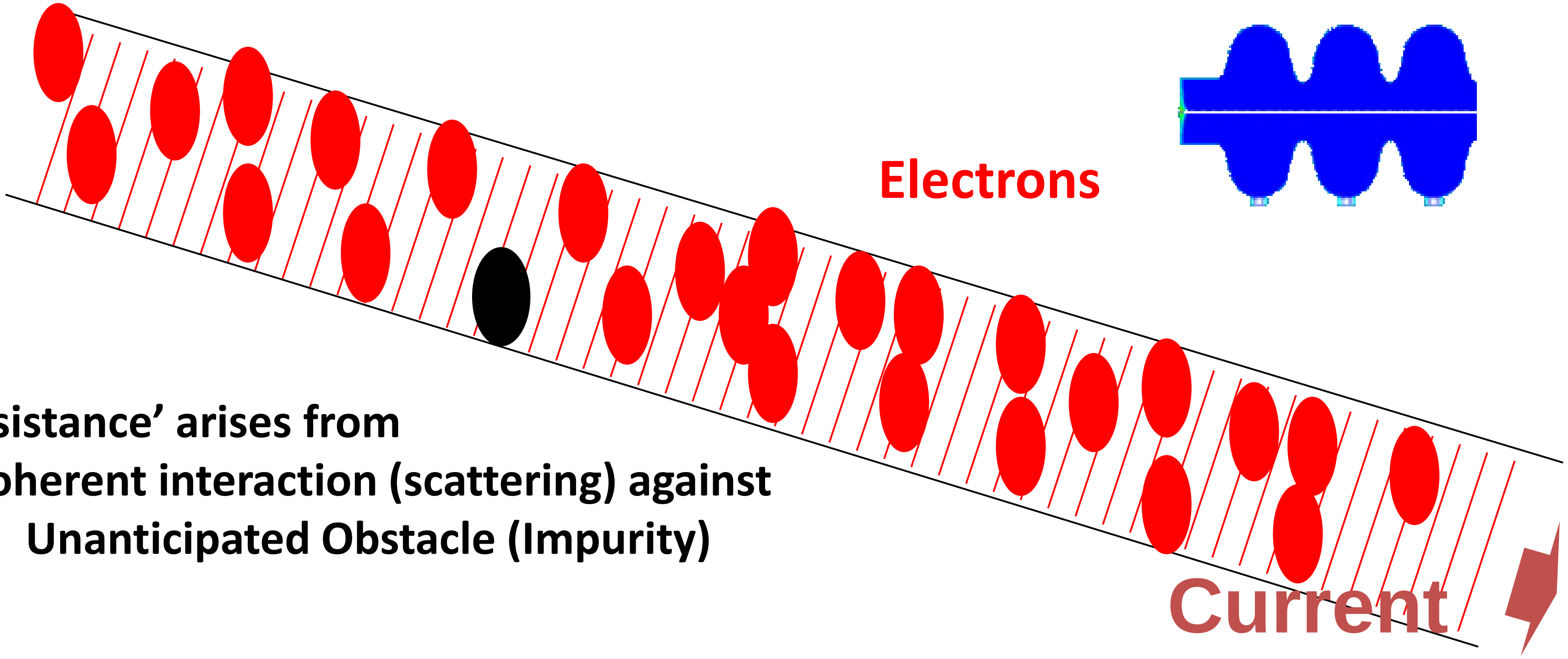
Creating macroscopic quantum systems and yet preserving long-lived quantum coherence is the key phrase in the future potential of Quantum Sensors….

→ Superconductivity plays a crucial role in many Quantum Sensor development

Left by itself Nature "decoheres" easily: clocks synchronized perfectly today will eventually show different times a few days later, due to slight differences in their running rates.

→ So, we need to work hard to maintain "coherence" in a classical setting already e.g. Laser-like coherent light generated in a freee electron laser .

Superconductivity – a quantum effect – critical to a large set of Quantum Sensors e. g. Superconducting electromagnetic cavities ringing forever!!



‘Resistance’ arises from
Incoherent interaction (scattering) against
Unanticipated Obstacle (Impurity)

Superconductivity = Super-fluidity of charge

Macroscopic collective (quantum) phenomena

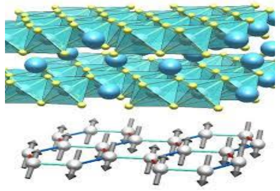
Quantum Sensors: APPLICATIONS

→ *Searches for New particles/Interactions: "Dark" Matter/Energy ****

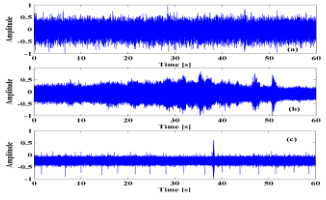
→ *Probes of the very early universe: Inflationary Cosmology ****

→ *Quantum Computers: Quantum Information Science*
CRYPTOGRAPHY, MARKET OPTIMIZATION, ARTIFICIAL INTELLIGENCE

→ *Bio-Signals (magneto-encephalography): Neuro-science ****

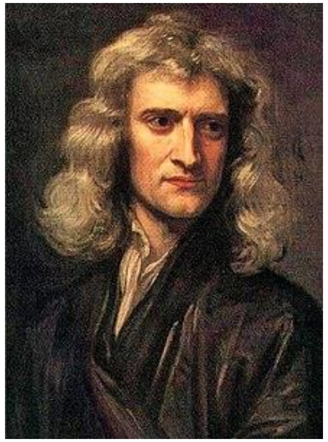


→ *New "strongly correlated" Materials: Material Science of*
*DESIGNER MATERIALS: "Dirac" and "Weyl" materials for particle and field detection ****



→ *Detection of "Weak" Environmental Signals: Geo-science*
CLIMATE CHANGE SCIENCE

**** I will briefly address these topics*



Thank You! For your Attention!!!!!!!!